

# Cost Model for End-Milling of AISI D2 Tool Steel

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**Abstract**—In this research paper, user-friendly and accurate mathematical model for estimating the cost of end-milling of AISI D2 tool steel using Polycrystalline Cubic Boron Nitride (PCBN) cutting tool inserts is developed. Initially, the different components of machining cost were identified, followed by establishment of equations to determine their values. Then, the required experimental and non-experimental data were collected and the bottom-up approach was adopted for evaluating the cost of machining corresponding to each of fifteen experimental runs. The Response Surface Methodology (RSM) was used to develop the model in which the cost of machining is given as a function of the machining parameters; cutting speed, feed per tooth, and depth of cut, and expressed in Ringgit Malaysia per cubic cm (RM per cm<sup>3</sup>). Analysis of Variance (ANOVA) was utilized to check the adequacy of the developed model. The developed model was found to be statistically adequate.

**Keywords**—machining cost; cost modeling; end-milling; RSM; AISI D2 tool steel.

## I. INTRODUCTION

With the advancement of technology, the problems of cost estimation, cost analysis and cost control have assumed great dominance in economic and engineering decisions. These factors are highly critical for the continued success of a manufacturing enterprise [1]. Cost estimates have several significant uses such as: to provide information to be used in establishing the selling prices [2].

Development of reliable cost models to estimate the cost of room temperature machining of AISI D2 tool steel at different levels of machining parameters; cutting speed, feed, and depth of cut, is a useful endeavor. Having cost models enables determining which cost elements contribute most to the cost; i.e. it can identify cost drivers. With cost model it is possible to determine the conditions that minimize cost (cost optimization).

In this research paper, the bottom-up and parametric cost estimation techniques were merged to develop a rather new technique that is free from the limitations of the parent techniques and inherits their advantages. The bottom-up and parametric cost estimation techniques are the most common in practice. They are the two main techniques from which several other techniques branch out [3].

The cost models found in the literature that can be used for estimating the cost of a machining run are generally less user-friendly, and having less capability to answer some important questions, beside this, they do not combine easiness-of-use with accuracy. These problems, through merging the bottom-up and parametric techniques, and modeling the cost of machining as a function of a small number of parameters for which data can be obtained rather easily, are efficiently solved.

## II. OVERVIEW OF PAST MACHINING COST MODELS

The past models of machining cost are generally descriptive; that is, they describe the cost components found in machining operations. This characteristic causes two problems: firstly, the model will be consisting of parameters for some of which data is not easy to obtain. Secondly, it will be consisting of many input parameters. Thus, it is not user-friendly. For instance, George E. D. [4] presented the following cost model which can be used to calculate the cost of an end-milling operation:

$$C_u = \frac{1}{60} \left[ \frac{M(1 + OH_m)}{100} + \frac{W(1 + OH_{op})}{100} \right] \left[ t_m \left( 1 + \frac{t_{tool}}{T} \right) + t_0 \right] + C_t \frac{t_m}{T} \quad (1)$$

$C_u$  = total unit cost, \$

$M$  = machine cost (depreciation, and maintenance, etc), \$/h

$OH_m$  = machine overhead (power, proportional share of building, taxes, insurance, etc), %

$W$  = labor rate for operator, \$/h

$C_t$  = tool cost, \$

$OH_{op}$  = operator overhead rate, %

$t_m$  = machining time

$t_{tool}$  = tool changing time

$T$  = tool life

$t_0$  = time elements that are independent of tool life

Obviously, this model is not user-friendly for finding the cost of a particular operation (or a run). It contains around ten input parameters for which the user has to find data. Besides containing many input parameters, data for some of these input parameters are not easily obtainable. For instance, any particular value of tool life is accompanied with a particular value of consumed power. Obtaining data of this pair is not readily easy. The model developed in this paper contains only three input parameters. The values for these parameters are chosen by the user (independent).

Similar models (to the one presented by George E. D.) were proposed by Robert C. C. et al. [2], Gavriel S. [5], Geoffrey B. and Winston A. K. [6], and others.

### III. RESEARCH METHODOLOGY

The methodology of this research can be outlined in form of the following activities:

- Establishment of equations to evaluate the cost of removing a unit volume of material (RM per cm<sup>3</sup>).
- Collection of all the data (experimental and non-experimental) required for evaluation of machining cost.
- Evaluation of machining cost considering 25% utilization.
- Use of RSM to model the cost of machining. ANOVA tables were used to check the adequacy of the developed model.

#### A. Establishment of Equations for Evaluating the Cost of Machining

In this research paper, the cost of machining is made up by the following cost components: operator cost, VMC depreciation cost, VMC maintenance cost, cost of electricity consumed by the VMC, tool edge cost, tool edge changing cost, and setup, loading, unloading, and teardown (SLUT) cost [2, 4, 5, 6].

Machining cost has been determined in terms of cost required to remove a unit volume of material (RM per cm<sup>3</sup>). Rather than evaluating the cost per component, determination of cost per unit volume of removed material can be more appropriate approach. Machining cost was evaluated considering a utilization level of 25%. This level of utilization is used in process-based facilities (e.g. job-shops). To reduce the truncation error, a long period (a span of one year) of production has been chosen for the calculation of machining cost.

During production time, the following activities are carried out: machine setup, work-piece loading, material removing, tool changing, work-piece unloading, and machine teardown. At 25% utilization, the production time per working day is 120 minutes (8 \* 60 \* 0.25). Out of these 120 minutes, 15 are used for setup, loading, unloading, and teardown (SLUT). These 15 minutes are equivalent to 3.125% ((15 / (8 \* 60)) \* 100) of the working day. The remaining working time in a day at 25% utilization level is (120 - 15) = 105 minutes. These 105 minutes are equivalent to 21.875% (25% - 3.125%) of the 8-hours working day. These 105 minutes are used for material removing and tool changing only.

In the established equations, the cost per cm<sup>3</sup> is obtained through dividing the yearly expense (RM) on a particular cost component by the yearly volume of removed material (cm<sup>3</sup>).

Based on this, the equation established to calculate operator's cost per cm<sup>3</sup> is as follows:

$$\text{Operator Cost per cm}^3 \left( \frac{\text{RM}}{\text{cm}^3} \right) = \left( \text{Operator's Salary per Year} \left( \frac{\text{RM}}{\text{yr}} \right) \right) / \left( \text{VMR per Year} \left( \frac{\text{cm}^3}{\text{yr}} \right) \right) \quad (2)$$

The volume of material removed (VMR) per year is calculated as follows:

$$\text{VMR per Year} \left( \frac{\text{cm}^3}{\text{yr}} \right) = \left( (250 * 8 * 60 * K \left( \frac{\text{min}}{\text{yr}} \right)) / ((\text{Tool Life} + \text{Tool Changing Time})(\text{min})) \right) * \text{Tool Life}(\text{min}) * \text{MRR} \left( \frac{\text{cm}^3}{\text{min}} \right) \quad (3)$$

K = 0.21875 (as elaborated above).

The VMC depreciation cost per cm<sup>3</sup> is obtained by the following equations:

$$\text{VMC Depreciation Cost per cm}^3 \left( \frac{\text{RM}}{\text{cm}^3} \right) = \left( \text{VMC Annuity} \left( \frac{\text{RM}}{\text{yr}} \right) \right) / \left( \text{VMR per Year} \left( \frac{\text{cm}^3}{\text{yr}} \right) \right) \quad (4)$$

The Annuity is calculated as follows:

$$\text{Annuity} = P * (i(1+i)^n / ((1+i)^n - 1)) \quad (5)$$

P = initial expenses of the VMC

i = cost of capital

n = useful life of the VMC

The cost of electricity consumed by the VMC per cm<sup>3</sup> is obtained by the following equation:

$$\text{VMC Electricity Cost per cm}^3 \left( \frac{\text{RM}}{\text{cm}^3} \right) = \left( \text{Electricity Consumed by the VMC per Hour} \left( \frac{\text{RM}}{\text{hr}} \right) \right) / \left( \text{MRR} \left( \frac{\text{cm}^3}{\text{hr}} \right) \right) \quad (6)$$

The VMC maintenance cost per cm<sup>3</sup> is obtained in a way similar to that of the operator's cost per cm<sup>3</sup>; this is through dividing the yearly expense on maintenance by the VMR per year.

The tool edge cost per  $\text{cm}^3$  is given by the following equation:

$$\text{Tool Edge Cost per cm}^3 \left( \frac{\text{RM}}{\text{cm}^3} \right) = \frac{\left( \text{Cost per Tool Edge (RM)} \right)}{\left( \text{Tool Life (min)} * \text{MRR} \left( \frac{\text{cm}^3}{\text{min}} \right) \right)} \quad (7)$$

The tool edge changing cost per  $\text{cm}^3$  is given by the following equation:

$$\text{Tool Edge Changing Cost per cm}^3 \left( \frac{\text{RM}}{\text{cm}^3} \right) = \frac{\frac{\text{Tool Edge Changing Time (min)}}{\text{Tool Life (min)} * \text{MRR} \left( \frac{\text{cm}^3}{\text{min}} \right)} * \left( \text{Operator Cost per min} \left( \frac{\text{RM}}{\text{min}} \right) + \text{Machine Cost per min} \left( \frac{\text{RM}}{\text{min}} \right) \right)}{\quad} \quad (8)$$

Operator cost per minute is given by the following equation:

$$\text{Operator Cost per Minute} \left( \frac{\text{RM}}{\text{min}} \right) = \frac{\left( \text{Operator's Cost per Year} \left( \frac{\text{RM}}{\text{yr}} \right) \right)}{\left( 250 * 8 * 60 * \text{Utilization} \left( \frac{\text{min}}{\text{yr}} \right) \right)} \quad (9)$$

The machine cost per minute is given by the following equation:

$$\text{Machine Cost per Minute} \left( \frac{\text{RM}}{\text{min}} \right) = \frac{\text{VMC Annuity} \left( \frac{\text{RM}}{\text{yr}} \right) + \text{VMC Maintenance Cost per Year} \left( \frac{\text{RM}}{\text{yr}} \right)}{250 * 8 * 60 * \text{Utilization} \left( \frac{\text{min}}{\text{yr}} \right)} + \frac{\text{Electricity Consumed by VMC per Minute} \left( \frac{\text{RM}}{\text{min}} \right)}{\quad} \quad (10)$$

Finally, setup, loading, unloading, and teardown (SLUT) cost per  $\text{cm}^3$  is given by the following equation:

$$\text{Setup, Loading, Unloading and Teardown Cost per cm}^3 \left( \frac{\text{RM}}{\text{cm}^3} \right) = \frac{\text{SLUT Time (min)} * \left( \text{Operator Cost per min} \left( \frac{\text{RM}}{\text{min}} \right) + \text{Machine Cost per min} \left( \frac{\text{RM}}{\text{min}} \right) \right)}{\left( \frac{(8 * 60 * K)(\text{min})}{\text{Tool Life} + \text{Tool Edge Changing Time (min)}} \right) * \text{Tool Life (min)} * \text{MRR} \left( \frac{\text{cm}^3}{\text{min}} \right)} \quad (11)$$

## B. Data used for Evaluation of Machining Cost

The data that were used to evaluate the cost of machining fall into two categories; experimental data [7], and non-experimental data. The non-experimental data are based on realistic assumptions and estimations. These data are shown in Tables 1 and 2.

Table I: The non-experimental data used for evaluating the cost of machining

Item	Specification
Operating days per year	250
Operating hours per day	8 of one shift
Utilization	25% and 90%
Operator's salary per year	RM 33600 (RM 2800 * 12)
Initial expense of the VMC	RM 300000
Useful life of the VMC	15 years
Cost of capital (%)	5
Depreciation method	Sinking fund
Yearly expense on VMC maintenance	RM 5000
Electricity tariff	RM 0.4 per kWh
Price per edge of cutting tool	RM 15
Tool changing time	5 minutes
Setup, loading, unloading, and teardown time	15 minutes

Table II: The experimental data used for evaluation of machining cost

Run No.	Cutting Speed (v) (m/min)	Feed (f) (mm/tooth)	Depth of Cut (d) (mm)	Tool Life (min)	MRR (cm <sup>3</sup> /min)	Electricity Cost per Hour (RM/hr)
1	134.20	0.025	1.63	14.99	0.300	0.0916
2	134.20	0.079	0.61	16.60	0.475	0.1073
3	78.30	0.079	1.63	20.32	0.750	0.1682
4	78.30	0.025	0.61	96.32	0.300	0.0179
5	102.50	0.044	1.00	7.53	0.325	0.0751
6	102.50	0.044	1.00	9.48	0.350	0.0751
7	102.50	0.044	1.00	7.53	0.325	0.0751
8	102.50	0.044	1.00	8.08	0.313	0.0751
9	102.50	0.044	1.00	9.11	0.325	0.0751
10	70.00	0.044	1.00	22.45	0.450	0.0513
11	150.00	0.044	1.00	3.81	0.350	0.1099
12	102.50	0.044	0.50	39.02	0.275	0.0344
13	102.50	0.044	2.00	5.57	0.350	0.1502
14	102.50	0.02	1.00	18.40	0.150	0.0313
15	102.50	0.1	1.00	2.58	0.575	0.1707

## C. Machining Cost Evaluated at 25% Utilization

Machining cost was evaluated considering 25% utilization level. The results are shown in Table 3.

Table III: Machining cost evaluated at 25% utilization

Run No.	Operator Cost (RM/cm <sup>3</sup> )	VMC Depreciation Cost (RM/cm <sup>3</sup> )	VMC Maintenance Cost (RM/cm <sup>3</sup> )	VMC Electricity Cost (RM/cm <sup>3</sup> )	Tool Edge Cost (RM/cm <sup>3</sup> )	Tool Edge Changing Cost (RM/cm <sup>3</sup> )	Setup, Teardown And Handling Cost (RM/cm <sup>3</sup> )	Machining Cost (RM/cm <sup>3</sup> )
1	7.8444	6.7478	0.0070	1.1673	73.5785	3.4514	1.9713	94.7678
2	6.4732	5.5682	0.0070	0.9633	56.1906	2.6361	1.6269	73.4652
3	3.9765	3.4206	0.0070	0.5917	29.4466	1.3821	0.9998	39.8243
4	28.3462	24.3834	0.0063	4.2182	52.4567	2.4593	7.1194	118.9895
5	11.8725	10.2127	0.0070	1.7667	177.6617	8.3330	2.9832	212.8370
6	10.8980	9.3745	0.0070	1.6217	141.1174	6.6190	2.7384	172.3759
7	11.8725	10.2127	0.0070	1.7667	177.6617	8.3330	2.9832	212.8370
8	11.5501	9.9353	0.0070	1.7188	165.5684	7.7658	2.9022	199.4475
9	11.0509	9.5059	0.0070	1.6445	146.8488	6.8878	2.7768	178.7216
10	12.7761	10.9900	0.0070	1.9012	87.2688	4.0925	3.2097	120.2454
11	11.2711	9.6954	0.0070	1.6772	239.8786	11.2538	2.8327	276.6158
12	16.0983	13.8478	0.0064	2.3956	68.5696	3.2152	4.0438	108.1766
13	6.7698	5.8234	0.0070	1.0074	120.0891	5.6357	1.7020	141.0343
14	19.9488	17.1600	0.0064	2.9686	159.8465	7.4948	5.0108	212.4359
15	9.2217	7.9325	0.0070	1.3723	228.11	10.7064	2.3187	259.6686

The machining parameters and their values that are presented in Table 2 are the factors (input variables) in modeling the machining cost, while the machining cost values that are presented in the last column of Table 3 is the response.

#### IV. RESULTS AND DISCUSSION

The Response Surface Methodology (RSM) was used for developing the model. The software Design-Expert 6.0.8 was utilized for this purpose. In the developed model, machining cost is expressed in terms of the machining parameters; cutting speed ( $v$ ), feed ( $f$ ), and depth of cut ( $d$ ).

Analysis of variance (ANOVA) was used to test the adequacy of the developed model. The adequacy was verified at 95% confidence interval. ANOVA output includes statistics such as “Prob > F” and “lack of fit” values. These were used to examine the significance of the model and its terms. “Prob > F” value that is less than 0.05 generally indicates significance at 95% confidence interval. If it is greater than 0.05, this generally indicates insignificance. Various types of  $R^2$  were used to examine the prediction capability of the developed model. Higher values of  $R^2$  indicate that the model is capable of explaining higher percentages of variability in the response. The adequacy of the developed model was confirmed by comparing the actual and predicted costs.

##### A. Formulation of Mathematical Model and Checking of Adequacy

Model 1 was developed for estimating the cost of machining (RM per cm<sup>3</sup>) in room temperature end-milling of AISI D2 tool steel at 25% utilization using PCBN cutting tool inserts.

$$\text{Log}_{10}(\text{Machining Cost}) = -36.96332 + 1.10294 * v + 44.50876 * f + 3.35536 * d - 0.010668 * v^2 + 44.22859 * f^2 - 0.45071 * d^2 - 48.70972 * f * d + 3.29433E-005 * v^3$$

Model 1

The ANOVA output of Model 1 (shown in Table 4) indicates that this Model is statistically significant and fitting for exploring the design space at 95% confidence interval.

Table IV: ANOVA output of Model 1

Response:	Machining Cost	Transform:	Base 10 log	Constant:	0
ANOVA for Response Surface Reduced Cubic Model					
Analysis of variance table [Partial sum of squares]					
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.72	8	0.090	70.92	< 0.0001
A	0.34	1	0.34	268.75	< 0.0001
B	0.28	1	0.28	221.94	< 0.0001
C	0.30	1	0.30	236.95	< 0.0001
A <sup>2</sup>	0.080	1	0.080	63.23	0.0002
B <sup>2</sup>	7.451E-003	1	7.451E-003	5.89	0.0514
C <sup>2</sup>	0.10	1	0.10	80.95	0.0001
BC	0.28	1	0.28	223.78	< 0.0001
A <sup>3</sup>	0.39	1	0.39	309.13	< 0.0001
Residual	7.501E-003	6	1.265E-003		
Lack of Fit	3.100E-004	2	1.550E-004	0.085	0.9200
Pure Error	7.281E-003	4	1.820E-003		
Cor Total	0.73	14			
Std. Dev.	0.036		R-Squared	0.9895	
Mean	2.16		Adj R-Squared	0.9756	
C.V.	1.65		Pred R-Squared	0.9196	
PRESS	0.058		Adeq Precision	30.513	

The “Prob > F” values of the Model and its “Lack-of-Fit” which are “< 0.0001” and 0.9200, respectively, prove that the Model is statistically adequate.

All the terms of the model (except the term B<sup>2</sup>) are significant at the 95% confidence interval as indicated by their “Prob > F” values which are all less than 0.05. The term B<sup>2</sup> is not significant, as indicated by its “Prob > F” value which is greater than 0.05. This term has been included in the Model because its removal adversely affects the adequacy of the model.

The “Pred R-Squared” of 0.9196 is in reasonable agreement with the “Adj R-Squared” of 0.9756 (within 0.2 from each other); this indicates that there is no problem; neither with the data nor with the Model. The “R-squared” value of 0.9895 indicates that the Model reasonably explains 98.95% of the variability of the machining cost.

The variation of the machining cost relative to the machining parameters is shown in Figure 1.

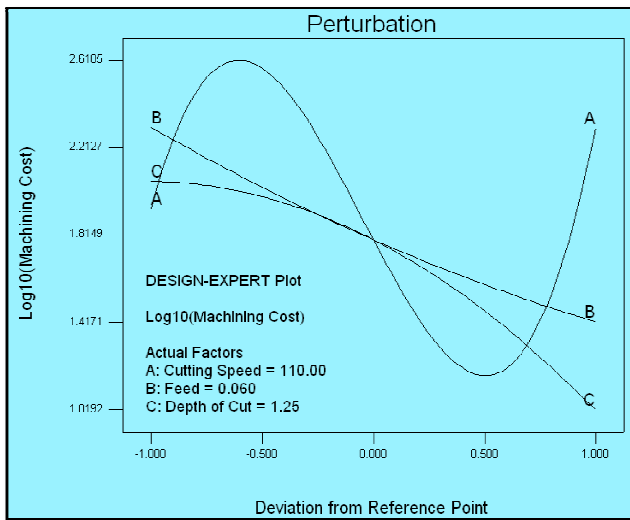


Figure 1. Perturbation plot for machining cost

By examining the equations that were established to calculate the values of the considered cost components, it can be seen that the cost of machining is influenced by three factors that vary with the machining parameters. These three factors are: tool life, material removal rate, and power consumption.

Tool life and material removal rate are located at the denominator of the cost components equations. Thus, as tool life and material removal rate increase, machining cost decreases. On the other hand, the cost of consumed power (RM per  $\text{cm}^3$ ) is a separate cost component that consists of the electricity cost per hour divided by material removal rate per hour. This cost component is added to the other components to obtain the cost of machining (RM per  $\text{cm}^3$ ). Thus, as it increase, the cost of machining increases, and vice-versa. This effect is opposite to the effect of tool life and material removal rate.

Generally, increase of cutting speed, tends to decrease the tool life, and this increases the cost of machining. On the other hand, as the cutting speed increases, material removal rate increases, this decreases the cost of machining. As cutting speed increases, the cost of consumed power might increase or decrease, thus, machining cost might decrease or increase. These opposing effects result in a particular pattern of variation of machining cost relative to the machining parameters.

Machining cost, as demonstrated by Figure 1, increases as cutting speed increases. This continues up to a cutting speed of about 90 m/min, then, it decreases as cutting speed increases. Again, this continues up to a cutting speed of 130 m/min, then, it increases as cutting speed increases. The larger portion of the relation between machining cost and cutting speed is that machining cost decreases as cutting speed increases.

Figure 1 indicates that the cost of machining decreases as feed and depth of cut increases. Machining cost, as demonstrated by Figure 1, appears to be very sensitive to cutting speed. Its sensitivity to the other two parameters is less.

Figure 2 indicate that the interaction between feed and depth of cut is significant.

Figure 3 indicate that optimal values of machining cost are obtained when the feed and depth of cut are at their highest levels or close to them, while the cutting speed is kept constant at 110 m/min.

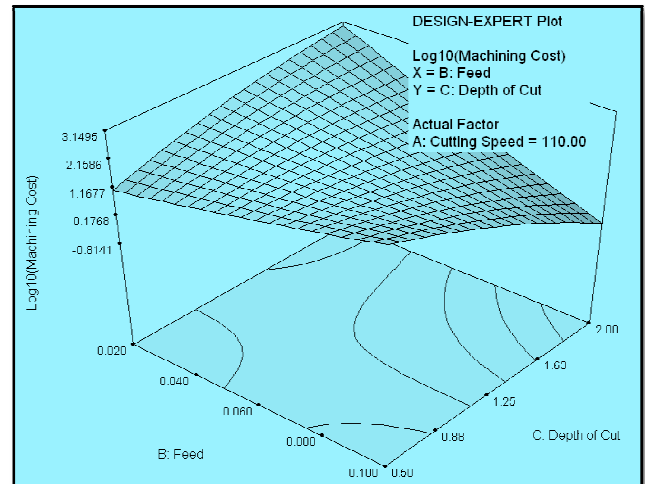


Figure 2. Response surface for machining cost vs. feed and depth of cut

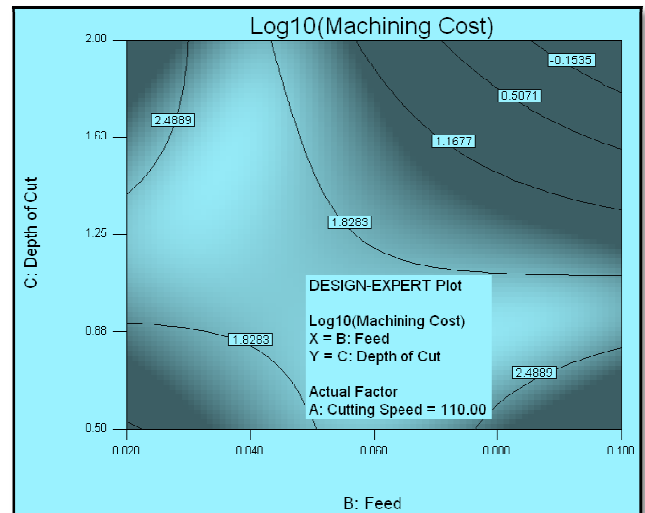


Figure 3. Contour plot for machining cost vs. depth of cut and feed

## V. CONCLUSION

In this research paper, user-friendly and accurate mathematical model to estimate the cost of end-milling AISI D2 tool steel using PCBN tool inserts is developed. This

model was developed based on 25% level of utilization. The ANOVA output indicated that the model is statistically adequate. For successful application of this model, it has to be used under the conditions that have been considered in developing it, such as the level of utilization, VMC initial expenses, operator's salary, and so on. This model can be used in cost reduction programs, process selection, and establishment of selling prices.

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